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FIRST OBSERVATIONAL EVIDENCE FOR CONDENSATION OF IO'S SO_2 ATMOSPHERE ON THE NIGHTSIDE

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ABSTRACT

The volcanically active Jovian satellite Io has a tenuous SO_2 atmosphere. The color of SO_2 is markedly different than the color of Io as a whole in the 0.4 to 0.6 μm region. We have exploited this fact to search Voyager 2 images for the condensation of SO_2 frost on its nightside. Measurements of the color of the dayside of Io, and the same geographical region at night. (illuminated by Jupiter's light), indicate that the night hemisphere is significantly bluer. The most likely explanation for this difference is that SO_2 frost. condenses on the surface during the night, and sublimates during the day. This is the first direct evidence for condensation of SO_2 frost on the nightside of Io.

The existence of Io's tenuous SO_2 atmosphere, and the evidence relating to that existence, have provided controversy in the field of planetary sciences for at least 20 years. In this paper we search for the condensation of that atmosphere on the night (Jupiter-illuminated) side of Io by observing color changes on Voyager 2 images. We find that the nightside of Io is consistently bluer than the same regions viewed under solar illumination. The most likely explanation for this color change is the condensation of SO_2 frost. This measurement is the first observational evidence for such condensation.

The first detection of atmospheric SO_2 by the Voyager IRIS instrument indicated an atmosphere in vapor-pressure equilibrium with the surface (1). Later detections of SO_2 atmospheric absorption bands in the ultraviolet by the Hubble Space Telescope (2) and in the millimeter region (3) were consistent with a collisionally dense atmosphere covering a fraction of the surface (8% in the first study and 5-20% in the latter). Given the variation of 4 orders of magnitude in SO_2 vapor pressure over Io's sunlit side (4), and the non-uniform distribution of SO_2 frost (5), an irregular atmosphere is reasonable.

Standard vapor pressure models for SO_2 predict a drop of more than 10 orders of magnitude between the day and night sides of 10 as the temperature drops from '130 K at the subsolar point to <70 K before dawn (2,4). Any SO_2 atmosphere should thus rapidly condense as the sun sets, With a nominal pressure of 10 nbar (3) a condensed atmosphere would provide a layer of condensed material about a micron thick, or about 10^3-10^4 molecules, easily detectable in the optical region of the spectrum. A recent laboratory study (6) shows that under Ionian conditions, SO_2 would survive for only 0.15 seconds at noon, but at dawn temperatures it should persist for 40 years. Finally, theoretical work on the dynamics of lo's atmosphere (7,8) demonstrate the plausibility of successive condensation and sublimation of Io's atmosphere on a diurnal time scale. All these pieces of evidence point to the condensation of Io's tenuous SO_2 atmosphere on the nightside, a phenomenon which should be detectable.

The relative distances of Jupiter and Earth from the sun constrain the maximum solar phase angle (the angle between the sun, the observer, and the target body) to be less than 12°: only a small sliver of Io's nightside is ever visible from the Earth, and it is not possible to obtain reliable photometric measurements on this small area which is poorly lit by Jupiter-shine. Another opportunity exists to briefly observe the surface of Io cooled by diminished sunlight. Io enters the shadow of Jupiter for about an hour and a half when it is eclipsed by that body. Some early observers reported post eclipse brightening, which they attributed to atmospheric condensation onto the colder eclipsed surface (e.g. , 9-13). Most evidence now seems to favor the absence of any condensations, at least for the majority of eclipses (14-16).

The only opportunity to observe the nightside of Io is with a spacecraft encounter . A series of images obtained during the Jupiter encounter by the Voyager 2 spacecraft over a two hour period as the solar phase angle changed from ‘100° to 150° provide an ideal sequence for studying the possibility that SO_2 frost condenses on the nightside of Io. The night regions were illuminated by Jupiter’s reflected light., so it is possible to obtain photometric measurements of these areas, which were also observed under daylight by the Voyager 2 spacecraft. Because 10’s nighttime lasts much longer than an eclipse by Jupiter does (˜21 hours, as compared to ˜2 hours), if the atmosphere of Io ever condenses out, this is where it will be seen. Although some early workers found evidence for localized enhancements of albedo on the nightside of Io (17,18), a comprehensive study (19) of such changes on the night hemisphere of Io failed to find any.

In this study we seek for the first time color, or spectral changes, rather than albedo changes between the day and nightsides of Io. The condensation on the nightside of $S0_2$ will leave a markedly bluer spectrum than that of a sunlit Io. This technique is capable of detecting global condensation of frost as well as the localized condensations that can be detected with albedo changes.

Figure 1 shows a spectrum of both Io and SO_2 frost. The frost has a considerably different spectrum than Io as a whole below ‘0.55 μm. Superimposed on the spectra are the positions of the four Voyager filters that most effectively measure color differences between a sunlit surface of Io and an unilluminated (i .e. , Jupiter- illuminated hemisphere covered with $S0_2$ frost.) The green (0.565 μm) and orange (0.59 μm) filters measure the “continuum” of the spectra, where they are nearly identical. The violet filter (0.42 μm) measures the spectra well into absorption band of Io’s integral spectrum, where $S0_2$ frost is still very bright, while the blue filter (0.485 μm) is on the edge of the absorption band. Color measured by the ratio of pairs of these filters (except for green and orange) is a sensitive indicator of spectral changes that could signify the deposition of frost on Io’s nightside. Table 1 quantifies the magnitude of the expected changes for specific color ratios; these quantities are best-case analyses for which the nightside of Io is coveredby an optically thick layer of SO_2 frost while the dayside is represented by Io’s integral spectrum.

A comparison of these color ratios for the dark hemisphere of Jupiter, compared with the same region under solar illumination, is clearly a powerful technique for detecting the condensation of SO_2 frost on the nightside of Io.

An additional correction must be made to account for the difference in the color of the solar spectrum and a redder Jupiter, which is illuminating the dark hemisphere of Io. 'l'his correction, which was calculated from the solar spectrum (20) and the Jovian spectrum (21) is listed in Table 1; it. is a fairly minor one compared to the magnitude of the change illustrated in Figure 1.

During the Voyager 2 encounter with Io 13 color sequences of the dark (Jupiter-illuminated) side of lo were obtained (Table 2). The identical regions were also imaged by the same spacecraft and filters under solar illumination; this sequence is the first one listed in Table 2. Color-ratio maps of the night, Jupiter-illuminated side of Io and the equivalent region under solar illumination were produced with the following steps (Each step for one of the ratios is illustrated in Figures 2 and 3):

1.. All images were recalibrated according to the latest files available at JPL's Multimission Image Processing Subsystem (MIPS). Particular attention was paid to the subtraction of dark current. We developed a technique to model the dark current of individual picture elements (pixels), rather than subtract a single number for an entire image. Values of the dark current in the region of Io's disk were computed by performing a bilinear interpolation to the values in an annulus surrounding Io.

2. For the nightside regions, images covering the same geographic region were co-added, to increase the signal-to-noise. The addition of these images presents a trade-off between increasing the signal and preserving the clarity of the image, since the spacecraft is moving and coregistration of surface features becomes problematical as time progresses. As a compromise, we constructed two sets of mosaics, One covers the second through fifth sequences listed in Table 2, which we call the low phase angle images, and the other covers the last 9 sequences , which we call the high phase angle images. The steps involved in processing the first group of images is illustrated in Figure 2 for the violet to blue color ratios, while the processing for the second group of images is shown in Figure 3.

3. images were mosaiced and projected into Mercator coordinates (see Figure 2 and 3, top two cells).

4. Maps of color ratios were obtained for the nightside and its equivalent region under sunlight for the following pairs of color maps: violet/blue, violet/orange , and violet/green. The two resulting maps are shown for the violet/blue filter in Figure 2, third cell (low phase angle observations) and 3,

third cell (high phase angle observations). For the nightside map, a portion of Io's disk illuminated by sunlight still appears.

5. Nightside to dayside ratios of each color map were obtained (Figures 2 and 3 bottom).

If no spectral changes on the nightside occur, the final color ratios of the nightside to dayside should all be unity, after corrections for the spectral differences between the sun and Jupiter. 'J'his is clearly not the case illustrated in the final maps at the bottom of Figures 2 and 3. At the terminator, there is a marked increase in the violet to blue color ratio, signifying that the nightside of 10 is significantly bluer than the dayside, The technique we describe is insensitive to color calibration factors for the Voyager camera, because in the final step, these factors cancel out.

Figure 4 illustrates this effect for the other color ratios, for both the series of images obtained at low phase angle and high phase angle. Table 1 lists the increase in the color ratio between the day and night hemispheres, after spectral corrections for the sun and Jupiter. These numbers were computed from a line of pixels extracted along the equator; Figure 5 illustrates two typical scans, for both low and high phase angle maps. For all cases, the nightside is significantly bluer than the dayside, and the amount of this spectral change, measured from Voyager images, is comparable to that expected if $S0_2$ frost covered the nightside. Figures 2, 3 and 4 also show that there is a tendency for the color ratio to increase at the nightside poles of Io. Enhanced deposition of $S0_2$ frost is expected at the poles not only because the surface is colder there, but because there is less SO_2 frost at the poles on the dayside (5).

The most plausible explanation for the change in color on the nightside of Io is the deposition of SO_2 frost there. Another possibility is the migration of the electronic absorption band of pure cyclooctal sulfur towards the blue end of the spectrum as the temperature drops (22). But studies in a wide range of fields have demonstrated that pure S_8 almost certainly does not exist on Io's surface , First, there is the geological evidence. The existence of silicates is implied by the high bulk density of Io (3.55 gm/cc). The size and persistence of geologic features on Io requires a tensile strength greater than that exhibited by pure S_8: siliceous components admixed with the sulfur probably provide this strength (23). High-temperature volcanic events (24) also point to significant amounts of silicates or other contaminants. Second, possible changes in the observed absorption band of 10's surface have been sought as a function of solar insolation angle (i.e., temperature), and none were found (22). Finally, processes such as sputtering by Jovian magnetospheric particles, bombardment by ultraviolet photons, and vacuum weathering have been shown to lead to the efficient destruction of S_8 (25-27).

'l'he condensation of the SO_2 frost is global (which is why they were not detected in the albedo maps (19)) and fairly rapid, in accordance with laboratory studies (6). Some regions, such as the SO_2-producing volcano Masubi located at (-45° latitude, 50° longitude) in the high phase angle image, clearly exhibit an enhanced amount of condensation at night.

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REFERENCES

1. J.C. Pearl *et al.*, *Nature* 280, 755 (1979).
2. G.E. Ballester *et al.*, *Icarus 111,* 2 (1994).
3. E. Lellouch, E. *et al.* *Icarus* 98, 271 (1992).
4. D.L. Matson and D. Nash, Journ. *Geophys. Res.* 88, 4771 (1983).
5. A.S. McEwen, T.V. Johnson, D.L. Matson, L. A. Soderblom, *Icarus 75,* 450 (1988) .
6, S.A. Sandford and L.J. Allamandola, *Icarus 106, 478 (1993).*
7. A.P. Ingersoll, M.E. Summers, S. G, Schlipf, *Icarus 64, 375 (1985).*
8. A.P. Ingersoll, *Icarus* 81, 298 (1989).
9. A.P. Binder and D. P. Cruikshank, *Icarus 3, ?99 (1964).*
10. T.V. Johnson, *Icarus* 14, 94 (1971).
11. B.T. O'Leary and J. Veverka, *Icarus* 14, 784 (1971).
12. B.T. O'Leary and E. Miner, *Icarus 20, 18 (1973).*
13. D.P. Cruikshank and R.E. Murphy, *Icarus 20, 7 (1973).*
14. J. Veverka, D. Simonelli, P. Thomas, D, Morrison, T.V. Johnson, *Icarus 47, 60 (1981).*
15. R. Nelson *et al.*, *Icarus 101,* 223 (1993).
16. J.J. Secosky and M. Potter, *Icarus* 111, *73 (1994).*
17. R. Terrile and A. Cook, Paper presented at IAU CoIl. 57, Kailua-Kona, HI, May 1980.
18. M. O'Shaughnessy, P. Helfenstein, J. Veverka, *Lunar Planet. Sci.* 20, 812 (1989) .
19. D.P. Simonelli, J. Boucher, P. Helfenstein, J. Veverka, D. M. O'Shaughnessy, *Icarus* 107, 375 (1994).
20. Allen, C. W. (1976). Astrophysical quantities. Athlone Press, London.

21. E. Karkoschka, *Icarus 111,* 174 (1994).
22. J. Gradie, J. Veverka, P. Thomas, J. Veverka, *Bull. Amer. Astron. Sot. 14, 735 (1982),*
23. M.H . Carr, H. Masursky, R.G. Strom, R.J. Terrile, *Nature* 280, 729 (1979).
24. T.V. Johnson *et al., Science 242, 1280 (1988).*
25. D.J. O'Shaughnessy, J.W. Boring, R.E. Johnson, *Nature 333, 240 (1988).*
26. R. Steudel, G. Holdt, A.T. Young, R. et al *Journ. Geophys. Res.* 91, *4971 (1986)* .
27. J. Moses and D. Nash, *Icarus 89, 277 (1991).*
28. D.B. Nash, F.P. Fanale, R.M. Nelson D., *Geophys. Res. Lett.* 7, 665 (1980).
29. D.P. Simonelli and J. Veverka, *Icarus 59,* 406 *(1984).*

Table 1 - Predicted and measured color changes for the dark side of Io

	Violet/Blue	Violet/Green	Violet/Orange
Predicted	2.0 ± 0.2	2.7 ± 0.3	2.7 ± 0.3
Low phase angle	2.8 ± 0.5	2.9 ± 0.4	2.9 ± 0.4
High phase angle	2.0 ± 0.2	2.1 ± 0.3	2.1 ± 0.3
Correction for Jovian spectrum	1.06	1.24	1.33

Table 2 - Voyager 2 images used in this study

Sequence FDS# start	Filters*	Lat(°)	Long(″)	Range(10^6 km)	Phase angle(″)
2059213	A	3	21-22	3.0	8.4-8.5
2065944	A	-6	10	1.1	102-103
2066000	A	-6	10	1,1	103-104
2066109	B	-6	8	1.1	109-110
2066133	B	-6	8	1.1	111-113
2066458	B	-6	17-19	1.1	129-132
2066545	B	-6	19-20	1,2	133-134
2066609	B	-6	20	1,2	134-136
2066633	B	-6	21	1.2	136-138
2066657	B	-6	21-22	1.2	138-140
2066721	B	-6	22-23	1.2	140-142
2066745	B	-6	23-24	1.2	142-144
2066809	B	-5	24-26	1.2	144-147
2066857	B; no green	-5	26	1.2	147-148

‘A consists of the following filters with effective wavelengths and bandwidths (FWHM) in μm: violet (0.42, 0.05), blue (0.485, 0.09), green1 (0.565, 0.07), and orange (0.59, 0.044). B consists of all A filters, plus the green2 filter, which is identical in specifications to the green1 filter.

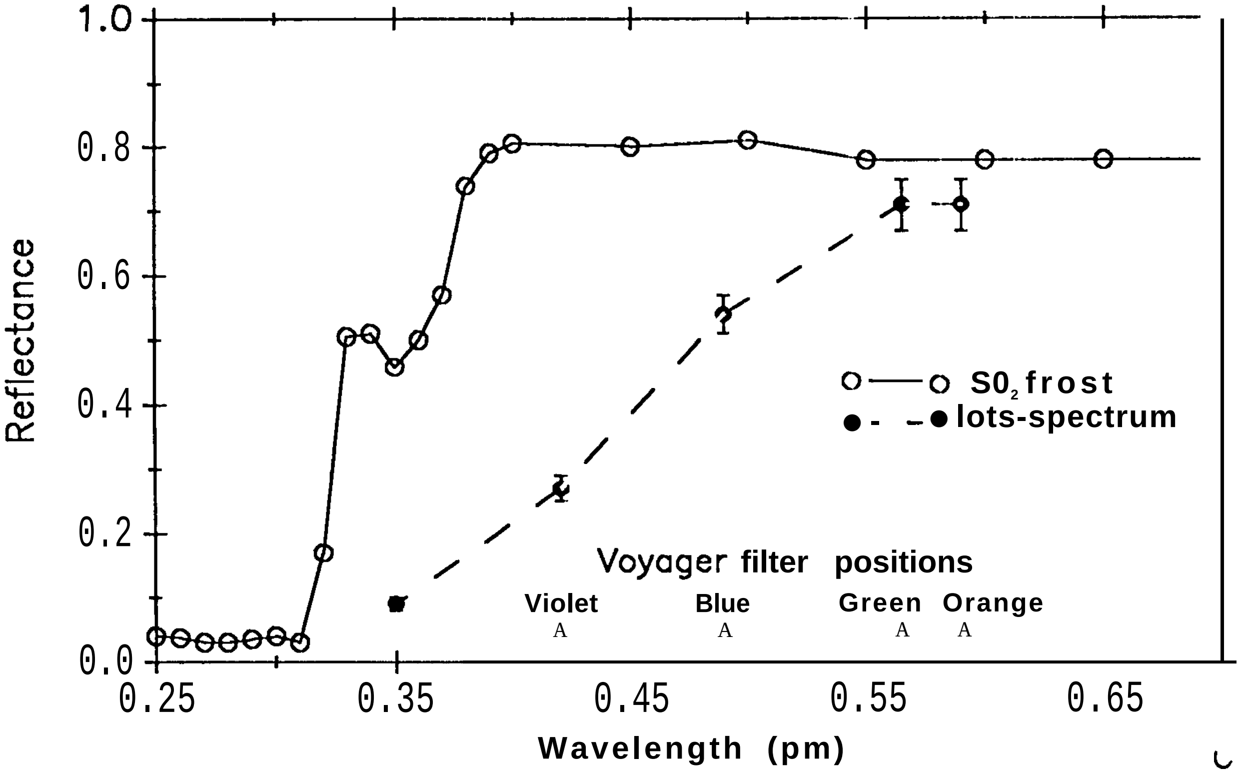
Figure 1. Spectra of SO_2 frost and disk-integrated Io compared with the placement of the Voyager 2 violet, green and orange filters. Data for SO_2 frost are from Nash et al. (28), and the data for Io are from Simonelli and Veverka (29).

Figure 2. A step-by-step illustration of tile processing involved in the comparison of the dayside and nightside color of Io. The top cell shows a blue mosaic of the nightside (right), and the equivalent region under solar illumination (left). For the nightside image the terminator appears at a longitude of about 20°. The second cell shows the blue map for the same regions. The third cell shows the violet-to-blue color map for the dayside (left) and the nightside (right). The bottom cell shows a ratio of these two maps to obtain a comparison of the color of day and night. The nightside is clearly bluer than the same region under solar illumination (the effect is enhanced by '6% if one accounts for the differences in the solar and Jovian spectra). Figure 4 gives a quantitative measure Of the increase.

Figure 3. Same as figure 2, except for the high phase angle sequences.

Figure 4. Final color ratio maps for the other filters, including images obtained at high phase angle and low phase angle.

Figure 5. An equatorial scan across the evening terminator of the final map in figure 2 and for the violet/orange color of the night and daysides at high phase angle, No corrections for the differences in solar and Jovian spectra have been made; Table 1 lists them. Errors are listed in Table 1 . (For clarity the top scan has been moved up two units).



1.0
0.8
0.6
0.4
0.2
0.0
Reflectance
0.25
0.35
0.45
0.55
0.65
Wavelength (pm)
SO_2 frost
lots-spectrum
Voyager filter positions
Violet
Blue
Green
Orange

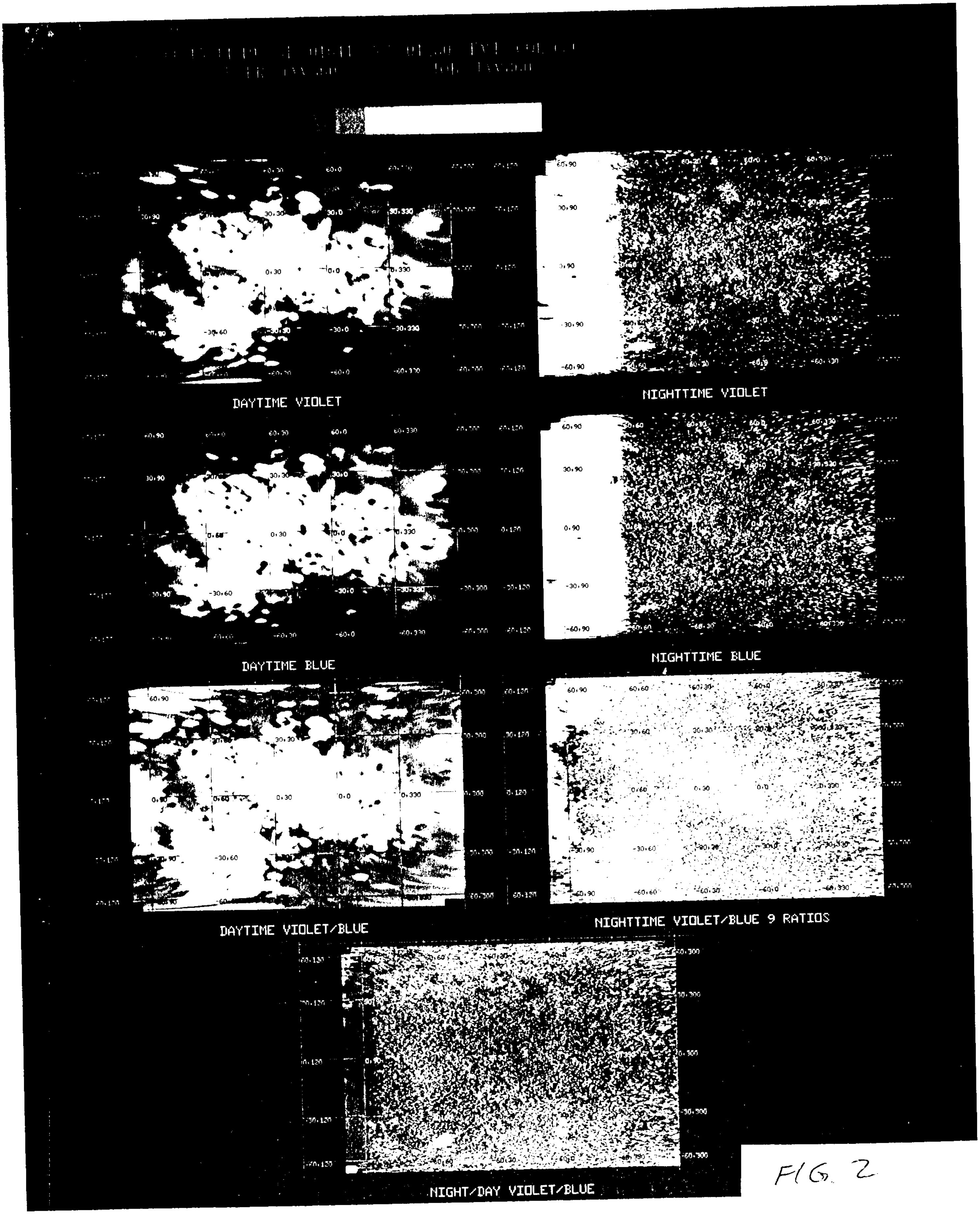

DAYTIME VIOLET
NIGHTTIME VIOLET
DAYTIME BLUE
NIGHTTIME BLUE
DAYTIME VIOLET/BLUE
NIGHTTIME VIOLET/BLUE 9 RATIOS
NIGHT/DAY VIOLET/BLUE

FIG. 2

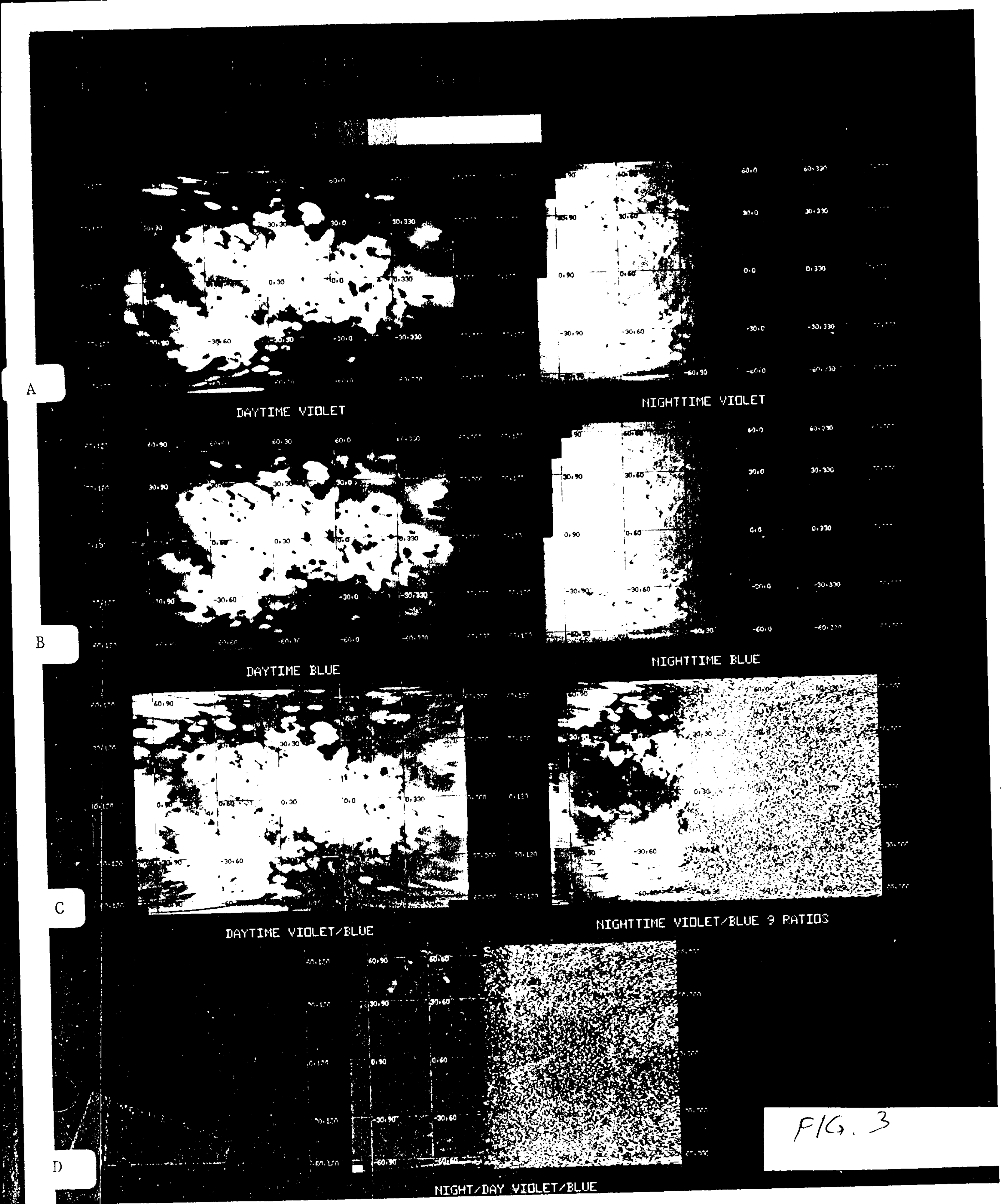

A
DAYTIME VIOLET
NIGHTTIME VIOLET
B
DAYTIME BLUE
NIGHTTIME BLUE
C
DAYTIME VIOLET/BLUE
NIGHTTIME VIOLET/BLUE 9 RATIOS
D
NIGHT/DAY VIOLET/BLUE

FIG. 3

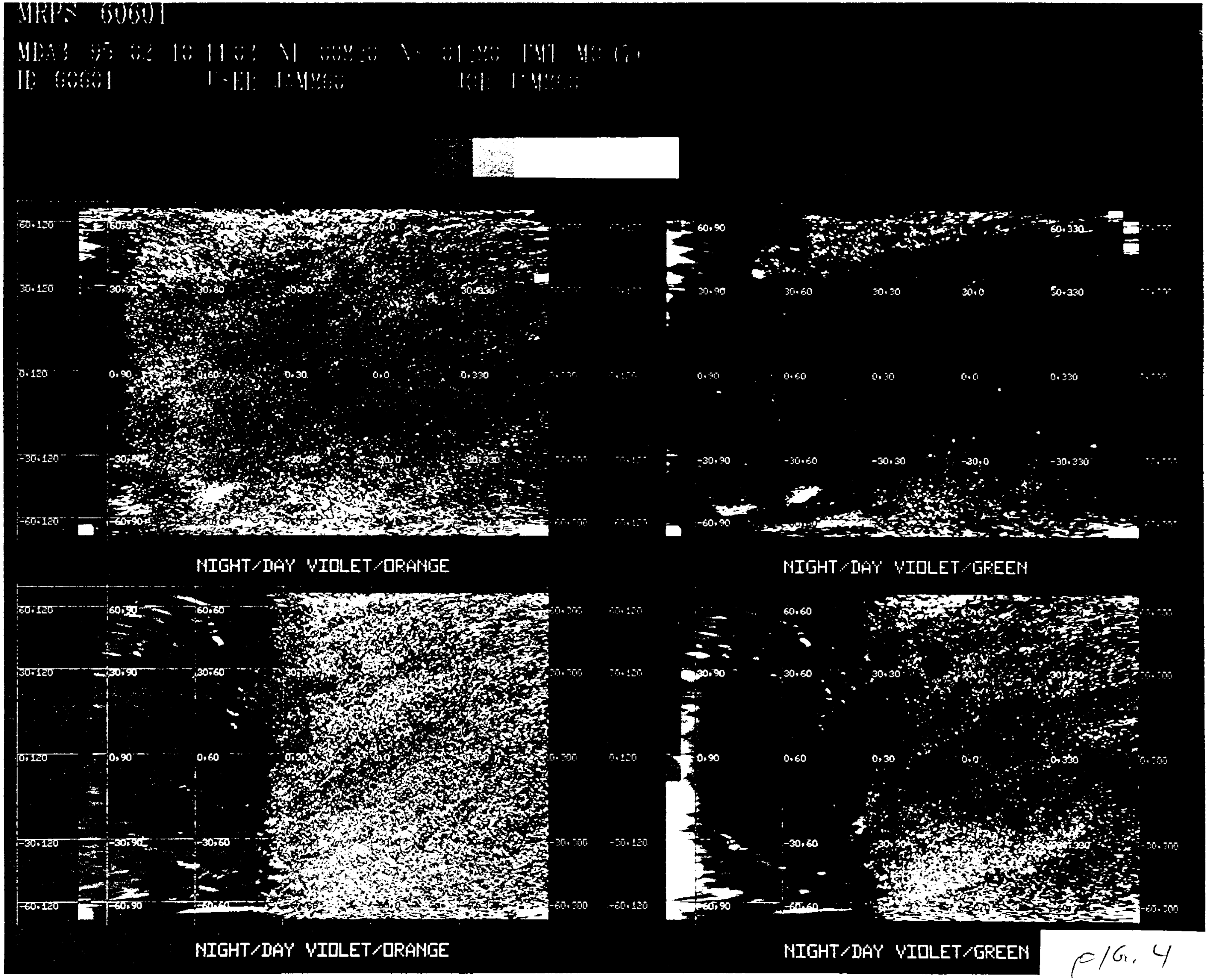
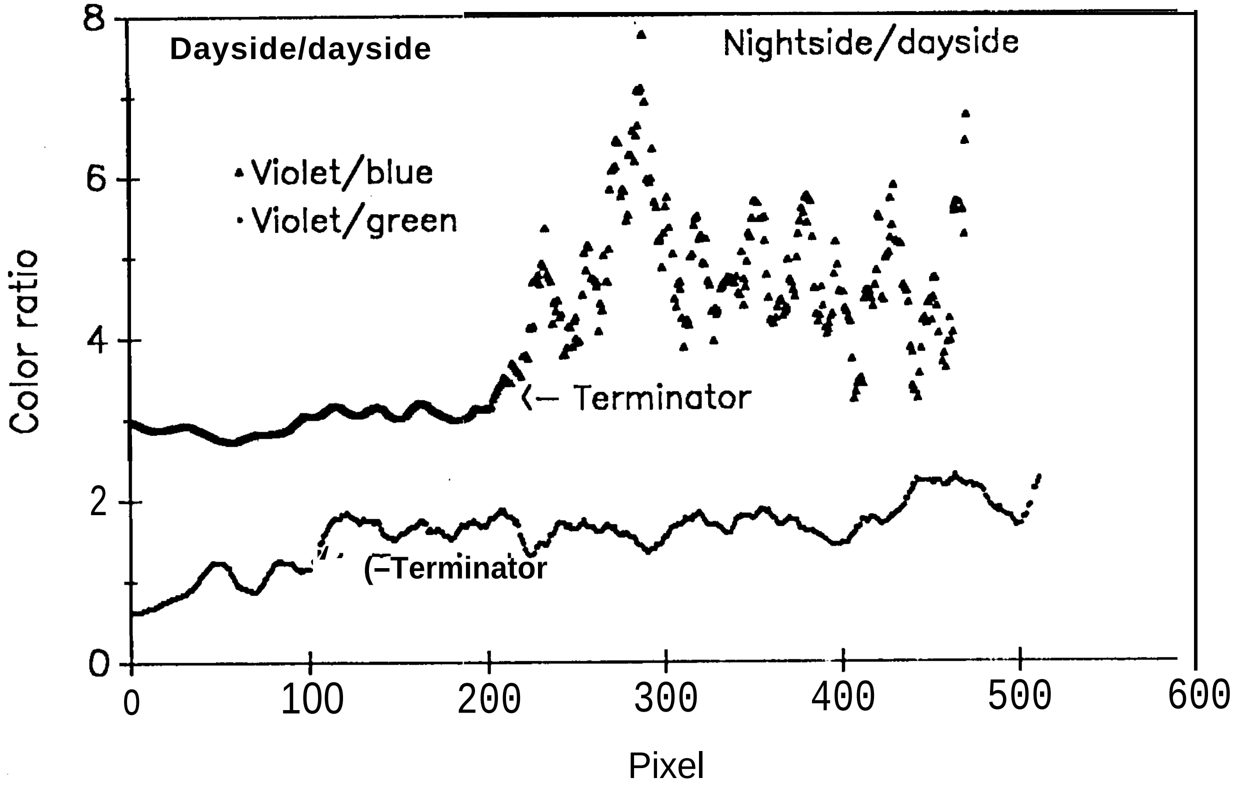

MRPS 60601
NIGHT/DAY VIOLET/ORANGE
NIGHT/DAY VIOLET/GREEN
NIGHT/DAY VIOLET/ORANGE
NIGHT/DAY VIOLET/GREEN

FIG. 4



Dayside/dayside
Nightside/dayside
Violet/blue
Violet/green
<— Terminator
(—Terminator
Color ratio
0
2
4
6
8
0
100
200
300
400
500
600
Pixel